

Content Addressable Memory Cell

This application is a Continuation-In-Part Application from pending U.S. Application Serial No. 09/894,900, filed June 29, 2001, ^{now US PAT 6,522,562} which claims priority from Canadian Application Serial No. 2,342,575, filed April 3, 2001.

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BACKGROUND OF THE INVENTION

Conventional content addressable memories (CAMs) are implemented primarily using static random access memory (SRAM) cells. SRAM-based CAMs have received widespread use due to the high access speed of SRAM memory cells and the static nature of the cells. Furthermore, SRAM cells can be manufactured using a pure-logic type fabrication process, which is commonly used for non-memory circuit blocks.

In addition to random access memory (RAM) functions of writing and storing data, the CAM also searches and compares the stored data to determine if the data matches search data applied to the memory. When the newly applied search data matches the data already stored in the memory, a match result is indicated, whereas if the search and stored data do not match, a mismatch result is indicated. CAMs are particularly useful for fully associative memories such as look-up tables and memory-management units.

Many current applications utilise ternary CAMs, which are capable of storing three logic states. For example, the three logic states are logic '0', logic '1' and "don't care". Therefore, such CAM cells require two memory cells to store the logic states, as well as a comparison circuit for comparing stored data with search data provided to the CAM.

In ternary form, each conventional SRAM-based CAM memory cell comprises a regular six-transistor (6T) SRAM cells. Therefore, SRAM-based CAM cells typically use 12 transistors to implement two 6T SRAM cells. That is, each SRAM cell requires 2 p-channel transistors and 2 n-channel transistors in a cross-coupled inverter relationship and a further 2 n-channel transistors as access devices from the bit lines.

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Furthermore, four additional transistors are required for each ternary CAM memory cell for implementing an exclusive-NOR function for comparing the search data with the stored data. For ternary CAM cells, n-channel devices are typically used in the comparison circuit.

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Some approaches in the art store data in a main memory cell and mask data in a mask memory cell. The comparison circuit is then either enabled or disabled by the mask memory cell contents. Examples of memory cells implementing such an approach are illustrated by U.S. Patent No. 6,154,384, issued to Nataraj et al. and U.S. Patent No. 6,108,227 issued to Voelkel.

10 Although this approach is functional from a circuit point of view, difficulty arises when attempting to layout the elements of the CAM cells. The main problem is a non-optimised layout of the CAM cell, which takes up more silicon area than desired.

15 DRAM-based CAMs have also been proposed in the art. DRAM cells are typically physically smaller than SRAM cells. Therefore, DRAM-based CAMs have the advantage of being able to store much more data than SRAM-based CAMs for a given area due to the much smaller CAM cell size. However, because of the dynamic nature of the DRAM cell, which is used to implement a DRAM-based CAM cell, such cells require regular refresh operations in order to maintain the data, and such refresh circuitry take up additional silicon area.

20 U.S. Patent No. 6,188,594 issued to Ong describes a CAM cell using only n-channel transistors. The CAM cell uses only n-channel transistors. The size of the cell is significantly reduced since the p-channel transistors are eliminated. The cell size is further reduced by using dynamic storage rather than static storage in the CAM cell. The dynamic CAM cell as described has as
25 few as six transistors, and a compact layout is facilitated. However, as previously mentioned, dynamic cells require additional refresh circuitry.

30 Therefore, there is a need for an SRAM-based CAM cell that achieves a more efficient spatial layout than the prior art, while maintaining the static characteristic of the SRAM-based CAM cell.

SUMMARY OF THE INVENTION

In accordance with an aspect of the invention, there is provided a content addressable memory (CAM) having a plurality of ternary memory cells fabricated in a semiconductor material, each ternary half cell comprising:

- 5 an equal number of transistors of a p-type and an n-type, the p-type transistors being formed in an n-well region and the n-type transistors being formed in an p-well region of said semiconductor material, the wells having at most one p+ to n+ region spacing, the transistors being interconnected to form the half ternary CAM cell and wherein the transistor interconnections are formed in a first group of layers and connections between the half ternary
10 cam cell and signal lines external to the cell are formed in a second group of layers.

BRIEF DESCRIPTION OF DRAWINGS:

Figure 1 is a circuit diagram of a ternary CAM half-cell according to an embodiment of the invention;

15 Figure 2 is a circuit diagram of a full ternary SRAM-based CAM cell according to a first embodiment of the invention;

Figure 3 is a circuit diagram of a full ternary SRAM-based CAM cell according to a second embodiment of the invention;

Figure 4 is a plan view of a half-cell layout corresponding to circuit in figure 1; and

20 Figure 5 is a circuit diagram of a full ternary SRAM-based CAM cell according to the prior art;

Figures 6(a), (b), (c), (d) and (e) show respective layers of layout of a mock layout of the ternary half cell of Figure 3 and

25 Figure 7 is a schematic diagram showing the arrangement of signal lines in the layout of Figure 6.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

- Referring to figure 5, an SRAM-based CAM cell that is standard in the art is illustrated generally by numeral 500. The CAM cell comprises two 6T SRAM cells 502. Each SRAM cell 502
30 comprises two p-channel transistors and two n-channel transistors in a cross-coupled inverter relationship 506, and a further two n-channel transistors 508 as access devices from a pair of bit

lines 510. The CAM cell further comprises a comparison circuit 512 with four additional n-channel transistors 508 for implementing an exclusive-NOR function for comparing search data with stored data.

- 5 The main problem with the implementation illustrated in figure 5 is an imbalance between the number of transistor types, which leads to a non-optimised layout of the CAM cell. Specifically, out of the total of 16 transistors, only four are p-channel devices. Moreover, all n-channel devices in a cell need to be positioned in a common p diffusion region. This region includes the n-channel access devices 508, the n-channels of the cross-coupled inverters 506 and the n-channels of the comparison circuit 512. The inevitable result is an unbalanced layout with regions containing the n-channels highly congested and wasted space around the two remaining p-channels used for the pull-up devices in the cross-coupled inverter transistors 504.

It is a well-known design layout rule in the industry that n+ to p+ spacing is usually large relative to other design rules in a typical CMOS fabrication process. Also, the n+ to p+ spacing cannot contain transistors therein. Therefore, the aspect ratio of the cell should be made narrow. That is, the smaller dimension of a typical cell is in the direction of the line of the p-well separating n-channels and p-channels in the cell array. This minimises the area wasted in the p+ to n+ spacing. However, this is difficult to achieve given the imbalance between n-type and p-type devices in the conventional approach.

- A reduction in ternary CAM cell area and optimization of a CAM cell layout is achieved by replacing n-channel access devices used for the SRAM cells with p-channel access devices and providing an active logic '0' activated word line instead of an active logic '1' activated word line. An SRAM cell with p-channel access devices is not normally used in conventional commodity or embedded SRAM applications due to the speed advantage of switching n-channel devices over p-channel devices. In a regular SRAM memory, the switching speed and other characteristics would suffer as a result. However, in a CAM cell, performance of the read/write is less critical than in a conventional SRAM cell since the primary task a CAM memory performs on a regular basis is a search and compare function.

Using p-channel access devices instead of n-channel access devices results in a full ternary CAM cell with a more balanced number of p-channel transistors and n-channel transistors. It is further preferable that the devices are balanced such that 8 n-channel devices and 8 p-channel devices are used in the layout.

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Referring to figure 1, a CAM half-cell in accordance with an embodiment of the invention is illustrated generally by numeral 100. The half-cell 100 comprises a complimentary bit line pair BL and \overline{BL} , a word line WL , a search line SL , a match line ML , cross-coupled inverter transistors P1, N1, P2, and N2 and p-channel access devices P3 and P4.

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P2 is coupled between a positive supply voltage 102 and a first node 104. N2 is coupled between the first node 104 and a ground supply voltage 106. Both P2 and N2 are gated by a second node 108. P1 is coupled between a positive supply voltage 102 and the second node 108. N1 is coupled between the second node 108 and a ground supply voltage 106. Both P1 and N1 are gated by the first node 104.

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The first node 104 is coupled to bit line BL via access transistor P3. P3 is gated by the word line WL . The second node 108 is couple to bit line \overline{BL} via access transistor P4. P4 is also gated by the word line WL . The p-channel access devices P3 and P4 selectively connect the cross-coupled inverters to complementary bit lines BL and \overline{BL} which carry read/write data.

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The match line ML is coupled to ground via serially coupled transistors N3 and N4. N4 is gated by the search line SL and N3 is gated by the second node 108. As can be seen from figure 1, there are four p-channel transistors and four n-channel transistors comprising the half-cell as opposed to two p-channel transistors and six n-channel transistors as discussed regarding the prior art approach.

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Referring to figure 2 a full ternary CAM cell in accordance with an embodiment of the present invention is illustrated generally by numeral 200. The full ternary CAM cell comprises 8 p-channel transistors and 8 n-channel transistors. The transistors of the first SRAM cell component of the full ternary CAM cell are numbered similarly to the corresponding transistors

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in figure 1 for convenience. For the second SRAM cell component of the CAM cell, the cross-coupled inverter transistors are labelled P12, N12, P11 and N11, the access transistors are labelled P13 and P14, and the transistors serially coupled between the match line ML and ground are labelled N14 and N13 respectively. It will be noted that for a full ternary CAM cell there are two complementary bit line pairs, $BL1$, $\overline{BL1}$ and $BL2$, $\overline{BL2}$ and two search lines $SL1$ and $SL2$.

The general operation of the full ternary CAM cell 200 illustrated in figure 2 is now described. To perform a write operation, data to be stored in the CAM cell is loaded onto bit line pairs $BL1$, $\overline{BL1}$, and $BL2$, $\overline{BL2}$. The word line WL is asserted active logic '0' turning on p-channel access transistors P3, P4, P13 and P14. The data carried on the complementary bit line pairs is thereby written into the two SRAM cells and the word line is de-asserted.

For a read operation, the complementary bit line pairs are precharged to $VDD/2$. The word line is asserted active logic '0' and the data from the SRAM cells is read onto the bit line pairs. The data then is transferred to data buses (not shown).

For a search and compare operation, the match line is precharged to logic '1' and data is placed on the search lines $SL1$ and $SL2$. Typically, search data and stored data are provided in such a manner that in the case of a mismatch a change occurs in the match line state. It is preferable to change the match line state for a mismatch rather than a match because a mismatch is a more infrequent occurrence. Therefore, a change in match line state will occur infrequently, reducing power dissipated by discharging match lines. The match line ML is precharged to a logic '1' and a mismatch discharges the match line to ground, whereas in the case of a match no change occurs in the state of the match line. Alternatively, in another match line sensing approach, the match line is precharged to logic '0' and detection of a match is made by pulling up with a device that is weaker than the two series devices holding the match line at logic '0'.

If the CAM cell 200 stores a logic '1' in the left SRAM cell and a logic '0' in the right SRAM cell, $SL1$ has logic '1', and $SL2$ has logic '0', a mismatch will result as follows. The output of the left SRAM cell provides a logic '1' to transistor N3, turning it on. The search line $SL1$

provides a logic '1' to transistor N4, turning it on. Since N3 and N4 are both turned on, they provide a path to discharge the match line *ML* to ground and thus indicate a mismatch.

5 If the CAM cell stores a logic '0' in the left SRAM cell and a logic '1' in the right SRAM cell, a match condition will result as follows. The output of the left SRAM cell provides a logic '0' to the gate of transistor N3, leaving it turned off. The search line *SL1* provides a logic '1' to the gate of transistor N4, turning it on. However, since N3 and N4 are serially connected, a path to ground does not exist for discharging the match line *ML* to ground. Similarly, the right SRAM cell provides a logic '1' to transistor N13, turning it on. The search line *SL2* provides a logic '0' to transistor N14, leaving it turned off. Therefore, similarly to the left SRAM cell, transistors N13 and N14 do not provide a path to discharge the match line *ML* to ground. As a result, the match line remains precharged to logic '1' indicating a match condition.

10 If the CAM cell stores a logic '0' in both the right and left SRAM cells a "don't care" state exists. The output from each SRAM cell produces a logic '0'. The logic '0' is provided to the gate of transistors N3 and N13, ensuring that a match condition is detected regardless of the data provided on the search lines *SL1*, *SL2*, and the match line remains unchanged.

15 This description of the basic operation only covers one possible match line detection scheme. However other approaches, including those common in the art as well as proprietary approaches, may be implemented without departing from the scope of the invention.

20 Referring to figure 3, an alternate embodiment of the invention is illustrated generally by numeral 300. In the present embodiment, access devices of the SRAM cells N23, N24, N33, N34 are n-channel devices and the transistors of the comparison circuit P23, P24, P33, P34 are p-channel devices. The operation is similar to the operation of the embodiment illustrated in figure 2 with the appropriate voltages reversed for devices of different polarities, as will be apparent to a person skilled in the art. For example, the word line *WL* is asserted active logic '1'. Further, the match line *ML* is logic '0' and a mismatch charges the match line *ML* to logic '1'.

Referring to figure 4, a layout of a ternary CAM half-cell in accordance with the present embodiment is illustrated generally by numeral 400. The layout 400 corresponds to the circuit 100 illustrated in figure 1. For convenience, the transistor labels given to the circuit of figure 1, that is P1, P2, P3, P4, N1, N2, N3, and N4, are used for indicating corresponding structures in the layout 400. In the layout 400, broken lines enclose regions representing active semiconductor areas 405 (for example, diffusion or ion-implanted areas). These areas include p-type active regions 405a and n-type active regions 405b. Thick, solid, continuous lines enclose a poly-silicon layer 410 while thin solid continuous lines enclose a metal 1 layer 420. The metal 1 layer 420 provides a metal interconnect between a plurality of metal contacts 404. The metal contacts 404 are represented by squares with an X symbol therein. Of special note is the metal 1 layer 420 connection for the cross coupled inverters formed by P2, N2, and P1, N1. Other higher metal layers (there are typically several metal layers) are not illustrated for simplicity. These include the search lines SL, complementary bit lines BL and \overline{BL} , which are in a third metal $M3$ layer. These and other layers will be apparent to a person skilled in the art.

As can be seen in figure 4 the p-channel devices P1, P2, P3, and P4 are grouped at the top of the figure, using a single n-well, while the n-channel devices N1, N2, N3, and N4 are grouped at the bottom, using a single p-well. This grouping results in a well-balanced use of cell area. Further, the compare circuitry N3 and N4 is separated spatially from the access devices P3 and P4, which yields a well-packed efficient layout with a desirably narrow aspect ratio. As such, only one p+ region to n+ region separation is necessary for the entire cell unlike prior art approaches which required at least two p+ region to n+ region separations. Further advantages of the layout described above include having the connections to the search transistors (N3, N4) at the opposite end of the connections to the access transistors (P3, P4). This separation eases congestion in the upper layers of metal. Furthermore, the cell is close to the minimum width set by transistor geometries, local interconnect (or metal 1), and upper metals simultaneously.

A minimal width and improved aspect ratio mean smaller area and reduced match line length, which is important to increasing speed and reducing power consumption. Analysis reports demonstrate that prior art approaches using a 0.13um pure logic process utilise a cell size that is

approximately 40% larger than a cell implemented using a layout in accordance with the present invention.

Referring now to Figures 6a, 6b, 6c, 6d and 6e, there is shown respective layers of a mock layout for half the ternary CAM cell circuit 300 of figure 3. As the layout corresponds to the circuit 300 illustrated in figure 3, the specific descriptions of the functions performed by parts of the circuit 300 are omitted. Also, for convenience, the same labels, P22, P21, P24, P23, N21-N24 are used to indicate corresponding structures in the layout.

More specifically, figure 6a illustrates regions of a silicon diffusion layer, a poly-silicon layer and a first metal layer M1; figure 6b shows second metal layer M2 overlaying layer M1; figure 6(c) shows a third metal layer M3 overlaying the layer M2; figure 6(d) shows a fourth metal layer M4 overlaying the layer M3 and figure 6(e) shows a fifth metal layer M5 overlaid on layer M4.

Referring back to Figure 6a, the half cell 300 includes P-diffusion regions 610a and 610b and N-type diffusion regions 612a and 612b, illustrated by regions enclosed with thick lines. The P-diffusion regions are U-shaped with regions 610a and 610b being separated. The N-diffusion regions 612a, 612b form a pair of outwardly turned L-shaped regions. The transistors P22-P24 are formed in the P-diffusion region 610a, while the transistor P21 is formed in the P-diffusion region 610b. The pair of drive transistors N22, N21 and their associated access transistors N23 and N24 are formed in the N-diffusion regions 612a, 612b, respectively. As may be seen, the P-diffusion region is created in the upper half of the layout while the N-diffusion region is separated from and created in the lower half of the layout. A mirror image (not shown) of the other half of the ternary cell 300 is repeated on the left side of the line of symmetry 605.

The respective gate electrodes of the transistors are formed by a layer of poly-silicon, indicated in figure 6a by a thick, continuous line enclosing dark stippled regions 620a, 620b, 620c and 620d. The poly-silicon layer 620a forms the gates of transistors P23, P22 and N22. Poly-silicon layer 620d forms the gates of transistors N23 and N24, poly-silicon layer 620c forms the gate of P24 and poly-silicon layer 620b forms the gates of P21 and N21.

The interconnection between the various transistors is accomplished in the first metal layer M1, indicated by lightly stippled regions. This metal layer M1 is laid over the poly-silicon layer 620. Interconnection between the diffusion or poly-silicon layers and the metal 1 layer M1 is achieved by metal 1 contacts, represented by cross-hatched rectangles.

The connection of the half ternary CAM cell to signal lines external to the cell such as match line ML, bit lines BL and BL\, search line SL, word line WL and supply lines VDD, VSS are achieved by interconnects made through contacts formed in the metal layer M1 and subsequent upper metal layers illustrated in figures 6b to 6e described in more detail below.

Accordingly, referring back to figure 6a, contacts formed in the metal layer M1 may be described as follows. VDD is provided to the P region 610a, 610b, through metal 1 M1 contacts 616a, 616b respectively. Similarly, VSS is provided to the N region 612a, 612b, through metal 1 M1 contacts 618a and 618b respectively. A search line (SL) contact 622 connects the poly-silicon gate of P24 to metal 1 M1 and the bit-line interconnect pads 623a, 623b connect the diffusion of transistors N23 and N24 to metal layer 1 M1 and are formed on the respective upper and lower peripheral edges of the layout schematic. The match line and word line contacts 624a, 624b are located at respective upper and lower right corners of the layout schematic.

Referring now to figure 6b, there is shown the interconnections between a second metal layer M2 and the first metal layer M1, with the second metal M2 being overlaid on the first metal layer M1. Interconnects between the layer M1 to M2 are indicated by the rectangular cross-hatched regions 629, while the conductive regions of metal layer M2 are indicated by the thin solid line diagonally-hatched shaded regions. Primarily, this metal 2 M2 layer is used to provide VDD, 630a and VSS, 630b signals to the cell array.

Referring now to figure 6c, there is shown a third metal layer M3 overlaid on the second metal layer M2, and indicated by stippled regions. Interconnects between the metal layer M2 and the metal layer M3 are indicated by diagonally hatched rectangular areas 639. The M3 layer primarily carries the search line 646 and Vdd. The remaining pads namely, the match line 633a,

and word line 633b are connected to the M2 layer through vias to corresponding pads 640a, 640b respectively. Similarly, the bit lines on M2 634a, 634b are connected through vias to pads on M3 at 644a, 644bB, respectively. Vdd is also connected from layer M2 630a, through a via to a pad 643 on layer M3.

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Referring now to figure 6d, there is shown the layout of the metal 4 layer M4 indicated by horizontally extending regions enclosed by lines, which are connected to the metal 3 layer M3 through metal vias shown by rectangular vertically-hatched regions 650.

- 10 Referring to figure 6e, there is shown the metal 5 layer M5, indicated by diagonally hatched regions comprising bit lines BL 662a, BL\, 662b connected through vias to metal pads 652a, 652b, respectively on metal layer M4.

15 Referring to figure 7, there is shown a schematic diagram of the major signal lines and their respective layers. Thus it may be seen that for each half cell layer as described in figure 6, the bit lines BL and BL\ extend along opposite sides of the half cell on metal layer M5, with the search line extending therebetween on layer M3. The match line and the word line ML, WL, extend orthogonally to the bit lines on layer M4.

20 Accordingly it may be seen that only one level of poly-silicon is used in this layout, with the signal and power lines formed in upper layer of metal. Thus the cell is more easily implemented using a straight "logic process". As is well known it is easier to create multiple layers of metal than multiple layers of poly-silicon.

- 25 Although the invention has been described with reference to specific embodiments, various modifications will become apparent to a person skilled in the art with departing from the spirit of the invention.